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FLIGHT RESEARCH ON NATURAL LAMINAR FLOW

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INTRODUCTION

[redacted] experiences with natural laminar flow (NLF) have provided a basis of understanding how this technology can be used for reduction of viscous drag on modern practical airplanes. The classical concerns about the practicality of NLF have related to achievability and maintainability. The earliest efforts to achieve NLF in flight were uniformly successful on specially prepared and gloved airframe surfaces, and unsuccessful on the production metal surfaces of the 1940's and 1950's era. More recent NASA flight experiments have demonstrated the achievability of NLF on modern metal and composite airframe surfaces. These experiments (refs. 1 to 6), more than 30 in total, were conducted over a range of free-stream conditions including Mach numbers up to 0.7, transition Reynolds numbers up to 14×10^6, chord Reynolds numbers up to 30×10^6, and on wings of relatively small leading-edge sweep angles, typically less than 27°.

In contrast to the difficulties encountered on older production airframe surfaces of the 1940's and 1950's, NLF is achievable today because of the small waviness of modern production wings, because of the lower values of unit Reynolds numbers at the higher cruise altitudes of modern airplanes, and because of the favorable influence of subcritical compressibility on two-dimensional laminar stability at the higher cruise Mach numbers of modern airplanes.

The significant implications of the past research are the following:

1. NLF is a practical drag reduction technology on modern metal and composite airframe surfaces for Mach numbers as high as 0.7, chord Reynolds numbers as large as 30×10^6 and wing sweep angles of 17° and 27° depending on length Reynolds number and unit Reynolds number.

2. NLF is more persistent and durable in typical airplane operating environments at high-speed subsonic conditions than previously expected.

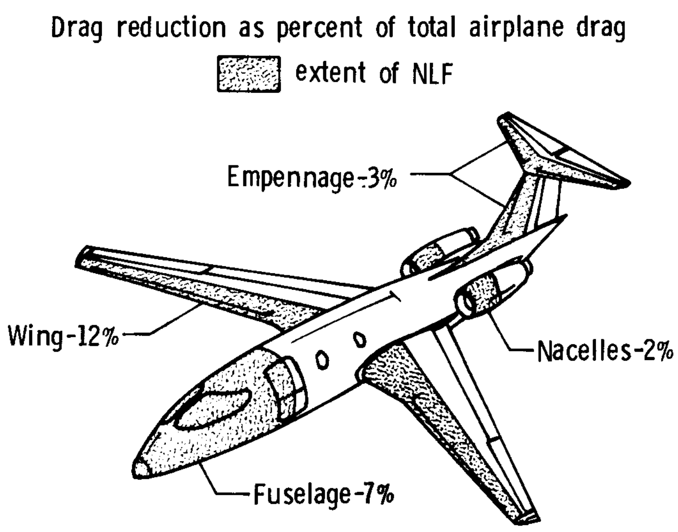
While the lessons of the past have been very instructive for current efforts to apply NLF to aircraft designs, research efforts continue to explore the limits of practical applications for NLF. These limits may be thought of in terms of combinations of maximum angles of sweep, Reynolds numbers and Mach numbers for which NLF can be achieved and maintained on practical airplanes in typical operating environments. Beyond these limits for NLF, laminar flow control (LFC) by suction appears as a promising means for achieving laminar viscous drag reduction benefits. This paper concentrates on NLF subjects.

NLF APPLICATIONS

Applications of NLF can include all surfaces of an aircraft. Favorable pressure gradients can be designed onto fuselages, horizontal and vertical tails and nacelles as well as the wings. For a high performance business jet, the potential drag reduction with NLF ranges between about 12 percent (for NLF on the wing only) to about 24 percent (for NLF on the wing, fuselage, empennage, and engine nacelles). These values of drag reduction are calculated as a percent of total airframe drag at a cruise Mach number of 0.7. Individual component benefits are tabulated below:

Component	% of Body Length NLF	% of Drag Reduction
Wing	50	12
Horizontal tail	30	2
Vertical tail	30	1
Fuselage	30	7
Nacelles	30	2
TOTAL:		24

These benefits can amount to large savings in fuel cost as well as increased performance. These drag reductions are calculated for NLF added to an existing configuration; larger benefits would accrue for integrated design calculations.

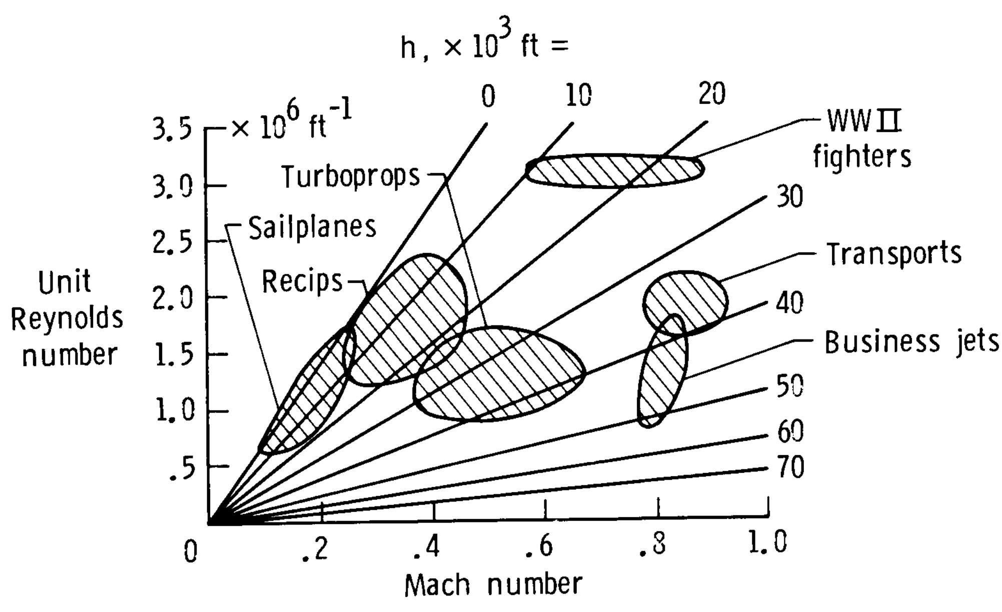


Total NLF drag benefit-24%

FAVORABLE EFFECTS OF CRUISE UNIT REYNOLDS NUMBER ON NLF ACHIEVABILITY AND MAINTAINABILITY

In recent years, two major trends in airplane fabrication methods and in airplane operational conditions have significantly aided laminar-flow achievability. First, modern airframe construction materials and fabrication methods produce aerodynamic surfaces which meet NLF requirements for roughness and waviness. These modern techniques include composites, milled aluminum skins, and bonded aluminum skins, among others. The second modern trend favorable to NLF is the smaller values of unit Reynolds numbers at which current business, commuter, and transport airplanes operate. The figure illustrates the flight conditions for these aircraft. Many modern high-speed airplanes cruise at unit Reynolds numbers less than 1.5 x 10^6 ft^{-1} (and some at less than 1.0 x 10^6 ft^{-1}) making the achievement of NLF-compatible airframe surfaces relatively easier than for older airplanes cruising at high speeds and lower altitudes. Early attempts to apply NLF were at unit Reynolds numbers sometimes exceeding 3 x 10^6 ft^{-1}. The resulting very thin, sensitive boundary layers at these conditions were far less tolerant of the roughness and waviness which existed on the older airframes. These conditions were responsible for the repeated failures of attempts to achieve and maintain NLF on the World War II fighter airplanes.

This realization has important implications for the maintainability of NLF on modern airplanes. Maintainability becomes significantly easier and less costly as unit Reynolds number decreases. Laminar flow has been a practical reality on sailplanes for decades, in large part because of the smaller value of unit Reynolds number experienced by these airplanes. As shown on the figure, unit Reynolds number decreases dramatically as altitude increases at constant Mach number. For example, an airplane flying at Mach = 0.8 at 40,000 ft experiences the same unit Reynolds number as a sailplane flying about 140 knots indicated airspeed at 10,000 ft. This comparison illustrates the relative improvements in achievability and maintainability of NLF resulting from the smaller values of cruise unit Reynolds numbers.



FAVORABLE COMPRESSIBILITY EFFECTS ON TOLLMIEN-SCHLICHTING GROWTH IN NLF

On swept wings, obtaining NLF requires a compromise between the need for damped Tollmien-Schlichting (T-S) growth by favorable pressure gradients and the conflicting requirement for limiting the growth of three-dimensional disturbances (crossflow vortices) by design of less favorable gradients. The growth rate of crossflow vortices is rapid in the region of rapidly falling pressure near the leading edge. Interaction can occur between the crossflow vortices and T-S waves to the detriment of laminar stability. The technical challenge to the successful design of swept NLF wings is to meet both of these conflicting pressure gradient design requirements and to avoid catastrophic growth of either the two- or three-dimensional instabilities. The successful NLF swept-wing design will achieve laminar runs at the design condition back to near the point of minimum pressure on the airfoil sections, with transition occurring either due to laminar separation or due to very rapid amplification of disturbances in the adverse pressure-gradient region.

Fortunately, nature provides assistance in meeting these conflicting design constraints for pressure gradients on swept NLF wings. As Mach number increases for a given pressure gradient, T-S wave growth and crossflow vorticity amplification rates are reduced by compressiblity effects. T-S wave growth, in particular, is significantly reduced by compressibility as illustrated in the figure. T-S amplification ratios, $n_{max} = n(A/A_o)$, were calculated for constant Mach number and increasing chord Reynolds number for the pressure distribution shown in the figure. These data show that n_{max} does not exceed 15 for even the largest value of chord Reynolds number (70×10^6). These predictions indicate that in dominantly two-dimensional compressible flows, transition by T-S instability may not occur prior to the point of minimum pressure on an airfoil even at higher Reynolds numbers. For the conditions analyzed here, even though the length Reynolds number is increasing, very little increase in compressible amplification ratio takes place. This phenomenon provides protection or enhancement of laminar boundary layer stability. Higher design Mach numbers are usually sought at higher altitudes, and since higher altitudes mean smaller unit Reynolds number, these two trends provide favorable influence for making NLF useful even at higher speeds.

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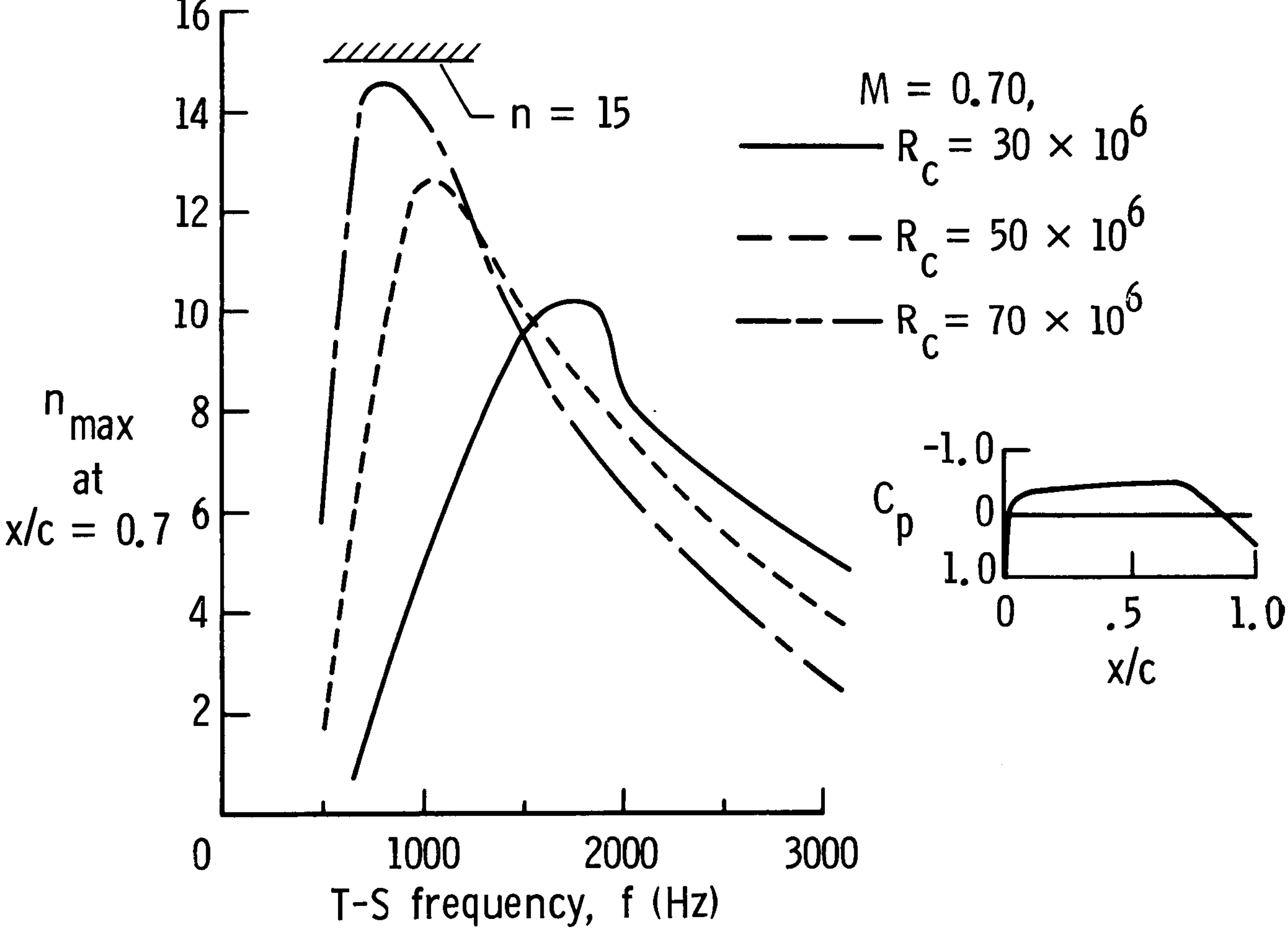
FAVORABLE INFLUENCE OF COMPRESSIBILITY ON 2-D NLF STABILITY



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CITATION III SWEPT-WING NLF FLIGHT EXPERIMENTS

Recent NLF flight experiments on the Cessna Citation III business jet have provided transition data useful for calibration of linear stability codes such as Malik's COSAL (ref. 7). Preliminary results from these 27° swept-wing experiments include two significant transition-location measurements; transition with minimum crossflow effect was observed at the pressure peak at 30-percent chord ($M = 0.7$, $R' = 1.2 \times 10^{6}\ ft^{-1}$), and was observed with significant crossflow effect, occurring well forward of the pressure peak at 10-percent chord ($M = 0.3$, $R' = 1.6 \times 10^{6}\ ft^{-1}$). It is encouraging that at the higher Mach number, transition occurred at or downstream or the pressure peak, indicating that NLF can be practical for swept wings at the flight conditions for business jet aircraft.

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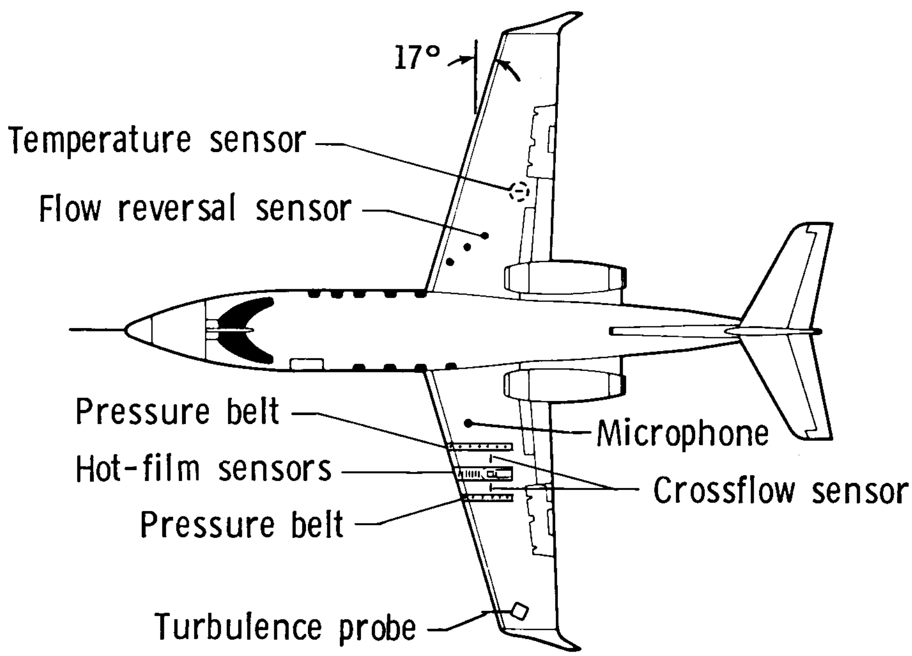
LEAR 28/29 NLF FLIGHT RESEARCH INSTRUMENTATION

The research instrumentation on the Lear 28/29 has been developed to document both location and mode of the transition on a moderately swept wing in compressible flow. Pressure belts containing 192 ports will be used to document the wing pressure distributions. A multi-element hot-film gage containing 25 hot-film sensors will be used to provide documentation of the locations of attachment line flow and transition. The hot-film data and pressure distribution data will be obtained simultaneously. Flow reversal sensors will be used to detect the presence of laminar separation as a cause of transition. Cross-flow hot-film sensors will be used to sense the presence of crossflow vorticity and transition in the laminar boundary layer. Both the flow-reversal and crossflow sensors are postage-stamp-size stick-on probes. Using these various methods will allow complete documentation of the transition phenomenon. Both the nature of transition and the location where the transition occurs will be determined.



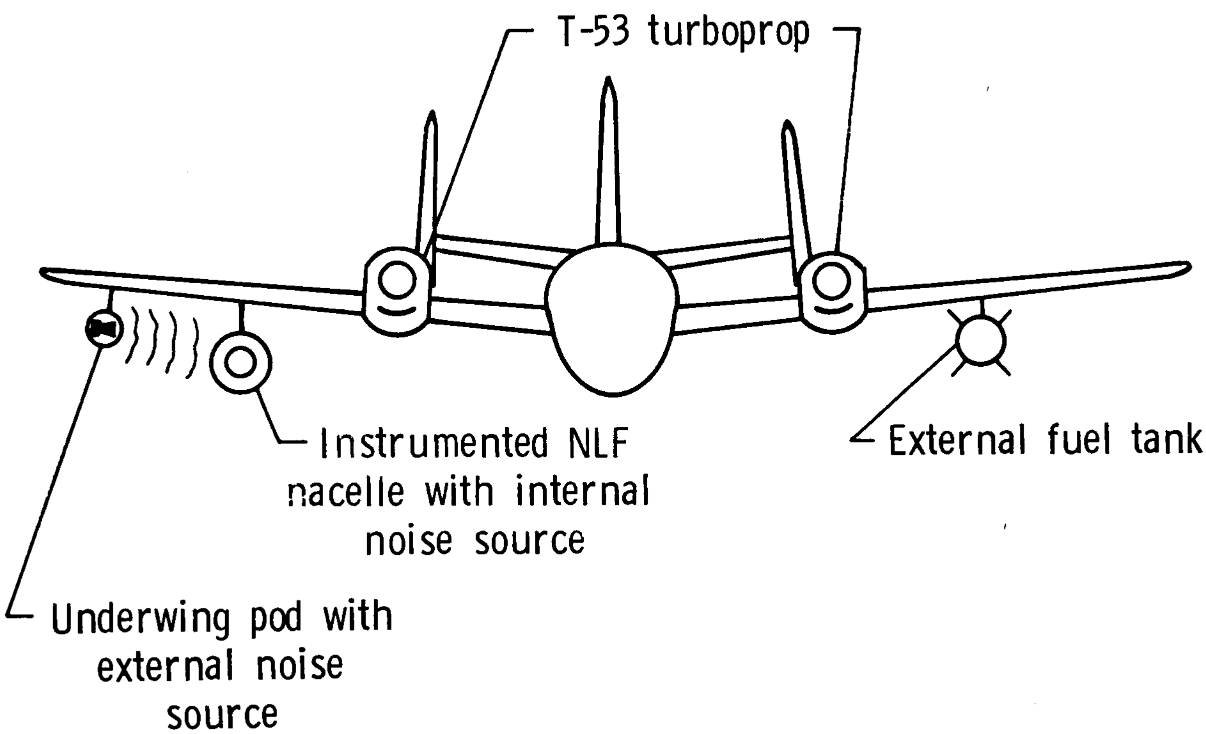
OV-1 NLF ENGINE NACELLE FLIGHT EXPERIMENTS

A series of flight experiments with NLF nacelles will be conducted using the NASA modified version of the Grumman OV-1 aircraft. The initial experiments will demonstrate the feasibility of NLF on a nacelle in the presence of jet engine noise. For these experiments, a laminar flow glove has been bonded to the existing nacelle. Transition and pressure distribution on the glove will be determined while laminar surface is exposed to acoustic disturbances from the JT-15D jet engine and an external noise source.

OV-1 NLF NACELLE FLIGHT EXPERIMENTAL CONFIGURATION

In the next phase of the laminar flow nacelle flight experiments, the existing JT-15D jet engine and nacelle will be removed, and three, flow-through NLF nacelle configurations (provided by General Electric) will be installed and flown. Both internal and external acoustic disturbance sources will be used to study the sensitivity of various boundary layer conditions to directivity, amplitude, and frequency of acoustic disturbances. The frequencies and sound pressure levels representative of large jet engines will be generated in flight by noise sources inside an underwing pod and in the NLF nacelle illustrated in the figure. For the second test configuration, three NLF nacelles with different pressure distributions will be flown individually to measure the laminar boundary layer stability under exposure to an external noise source. Transition will be documented during these flights using surface-mounted hot-film gages. Correlations with existing empirical transition criteria will provide improved confidence in the use of these criteria for design of larger scale NLF nacelles.

The objectives of these experiments are to demonstrate NLF feasibility in representative engine noise environments and to broaden the base data for prediction of the effects of engine-generated acoustic disturbances on boundary layer transition in the flight environment. The NLF nacelles will be instrumented with microphones for surface noise measurements, hot-film strips to determine transition locations, and pressure ports of measurement of surface pressure distribution.

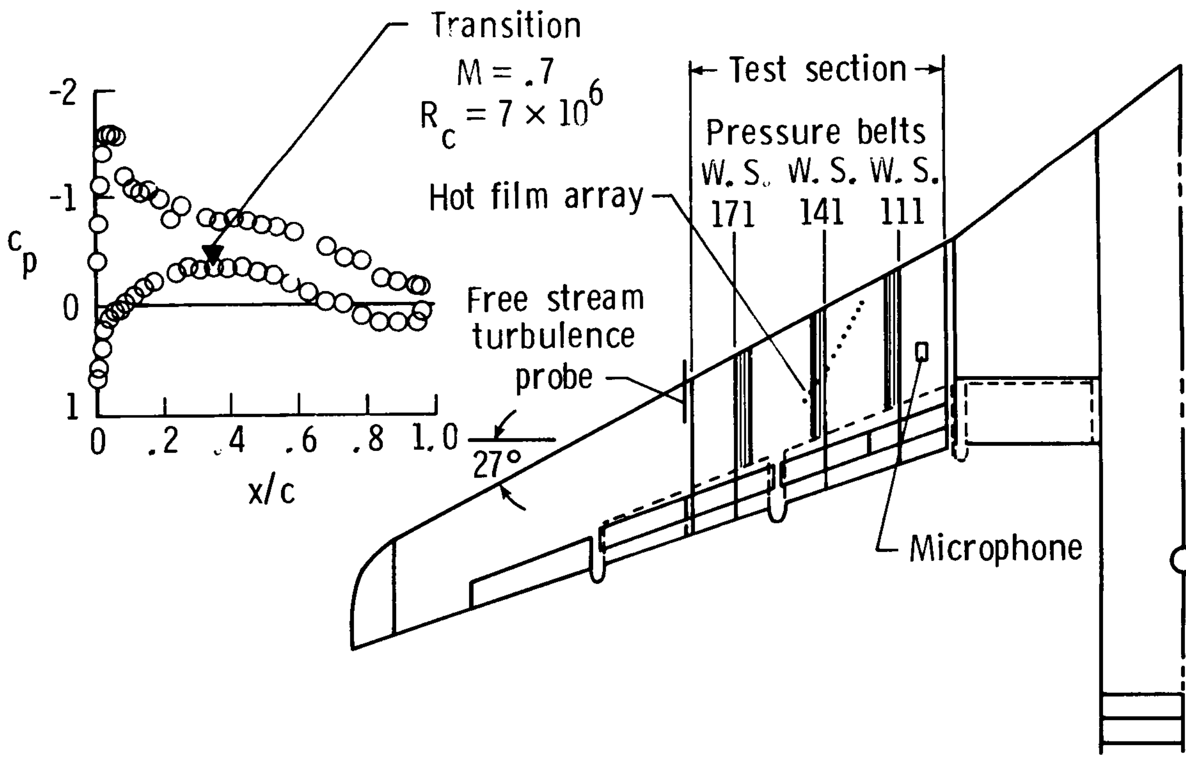


LEAR 28/29 VISCOUS DRAG REDUCTION FLIGHT RESEARCH PROJECT

NLF flight experiments are planned on the Lear 28/29 turbojet business airplane. The Lear 28/29 has extensive laminar flow on its wing and provides free-stream conditions ($M = 0.8$, $h = 51,000$ ft, $R' = 3 \times 10^6$ ft^{-1}) suitable for NLF research applicable to a wide variety of aircraft types. Wing leading-edge sweep is 17°; with an additional 7° of sweep available by side-slipping the airplane, a total of 24° can be tested. For these flight conditions, both the determination of the nature of transition as well as the development of laminar boundary layer transition visualization methods will be attempted. Correlations of measurements with linear compressible stability theory will provide improved calibration for the use of such methods for NLF swept surface designs.

CITATION III NLF SWEPT-WING FLIGHT EXPERIMENTS

Flight experiments were conducted on the Cessna Citation III turbofan business airplane to measure the location and behavior of transition on a smoothed test section of the 27° swept wing. Surface hot-film transition sensors and sublimating chemical transition visualization were used. Surface pressure distributions were measured using pressure belts. Engine noise was monitored with a microphone attached on the upper surface of the test wing. This was done to investigate any possible effects of engine-generated acoustic disturbances on the wing laminar stability. Sideslip conditions were flown to effectively increase and decrease the leading-edge sweep angle and thus affect amplication of crossflow vorticity. Analysis of linear uncoupled stability of the laminar boundary layer has been conducted.



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